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14. ABSTRACT
To achieve the goal of the proposal, we created nano-structured surfaces to increase the pixel density and hence resolution of the opto-electronic sensor array by a factor of 3 in each direction, x and y. The proof of concept of this mathematical framework in the visible part of the optical spectrum was published in 2 journal articles (both published in Applied Physics Letters). In addition to this, we also experimentally applied the same concept to IR part of the optical spectrum and thus demonstrated the feasibility of our approach for IR focal plane arrays. These results will be presented at SPIE Defense, Security and Sensing Conference in April 2012.

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Grant/Contract Number: FA9550-09-1-0199

PI: Aydogan Ozcan, UCLA;   Program Manager: Dr. Arje Nachman

Final Report:

In our proposal we aim to demonstrate the use of nano-structructed surfaces to passively increase the pixel density of low pixel count sensors. This approach utilizes multi curve variate analysis tools as well as compressive decoding algorithms to digitally increase the pixel resolution using a specially designed and calibrated nano-structured surface. A significant impact of this approach will be in IR sensor-arrays since it is technically quite challenging and expensive to make high-pixel-count sensors in this part of the electromagnetic-spectrum. However, application of the same concept to other parts of the spectrum is also feasible broadening the overall impact of this project.

To achieve this goal of the proposal, we created nano-structured surfaces to increase the pixel density and hence resolution of the opto-electronic sensor array by a factor of 3 in each direction, x and y. The proof of concept of this mathematical framework in the visible part of the optical spectrum was published in 2 journal articles and 2 conference presentations (see our list below). In addition to this, we experimentally applied the same concept to IR part of the optical spectrum and thus demonstrated the feasibility of our approach for IR focal plane arrays. These results will be presented at SPIE Defense, Security and Sensing Conference in April 2012.

For this IR demonstration work we fabricated nano-structured chips using focused ion beam milling as demonstrated in the picture below, where the structured surface is placed in close proximity of an IR sensor-array with a vertical spacing of ~0.2mm.
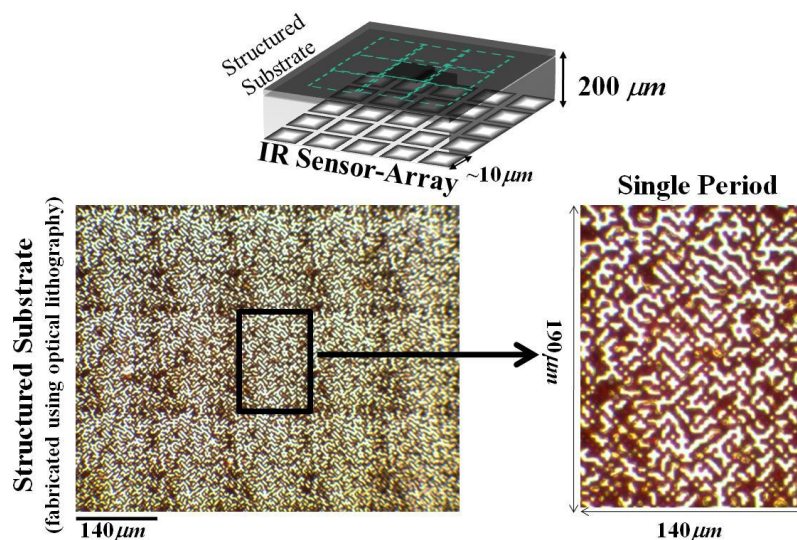
This nano-structured chip is designed using finite-difference time domain simulations to ensure that within each period of the structured chip, the IR sensor-array captures a unique pattern that can then be used to decompose any arbitrary intensity distribution into a higher resolution image.
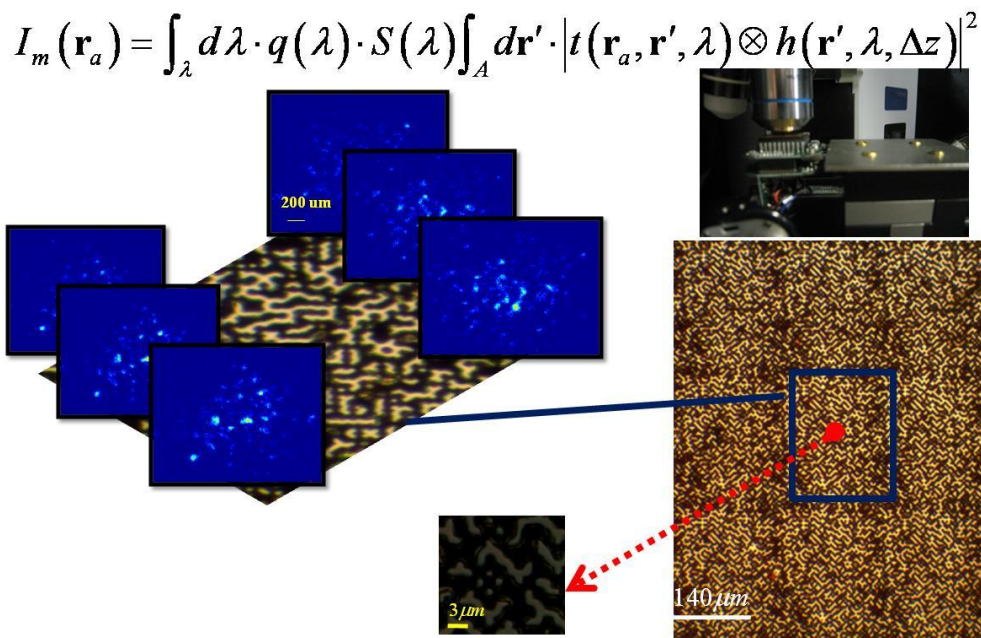
The first step after this design and fabrication step was to calibrate the fabricated chip using a scanning based system that record the lensless diffraction pattern of each point on the structured surface to measure the basis of each period. This is experimentally achieved using the set-up that is illustrated below:

A sub-micron calibration spot precisely scans the structured chip in 2D using a piezo stage while calibration frames are acquired.
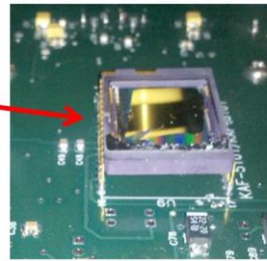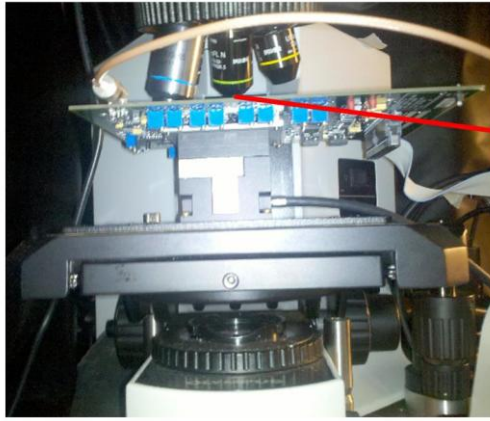
The nano-structured surface is fabricated using FIB and is placed on the sensor-array.

As a result of this scanning based calibration step (which is required only once for a given chip), a lensfree image is acquired for each spot on the nano-structured chip which will then be used to decode any arbitrary intensity pattern that hits the structured surface into a much higher resolution image, which is conceptually summarized below:

$$I_m(\mathbf{r}_a) = \int_\lambda d\lambda \cdot q(\lambda) \cdot S(\lambda) \int_A d\mathbf{r}' \cdot \left| t(\mathbf{r}_a, \mathbf{r}', \lambda) \otimes h(\mathbf{r}', \lambda, \Delta z) \right|^2$$

We have experimentally tested our approach by resolving sub-pixel IR intensity patterns that would normally be under-sampled using the raw IR sensor-array, such that the center to center spacing between IR spots was smaller than the pixel pitch size at the sensor chip. By using compressive sampling based reconstruction algorithms (that involve l_1 regularized least square optimization) we were able to resolve IR objects that we have artificially created with much higher resolution than the raw sensor would normally permit. Our experimental IR results are summarized below
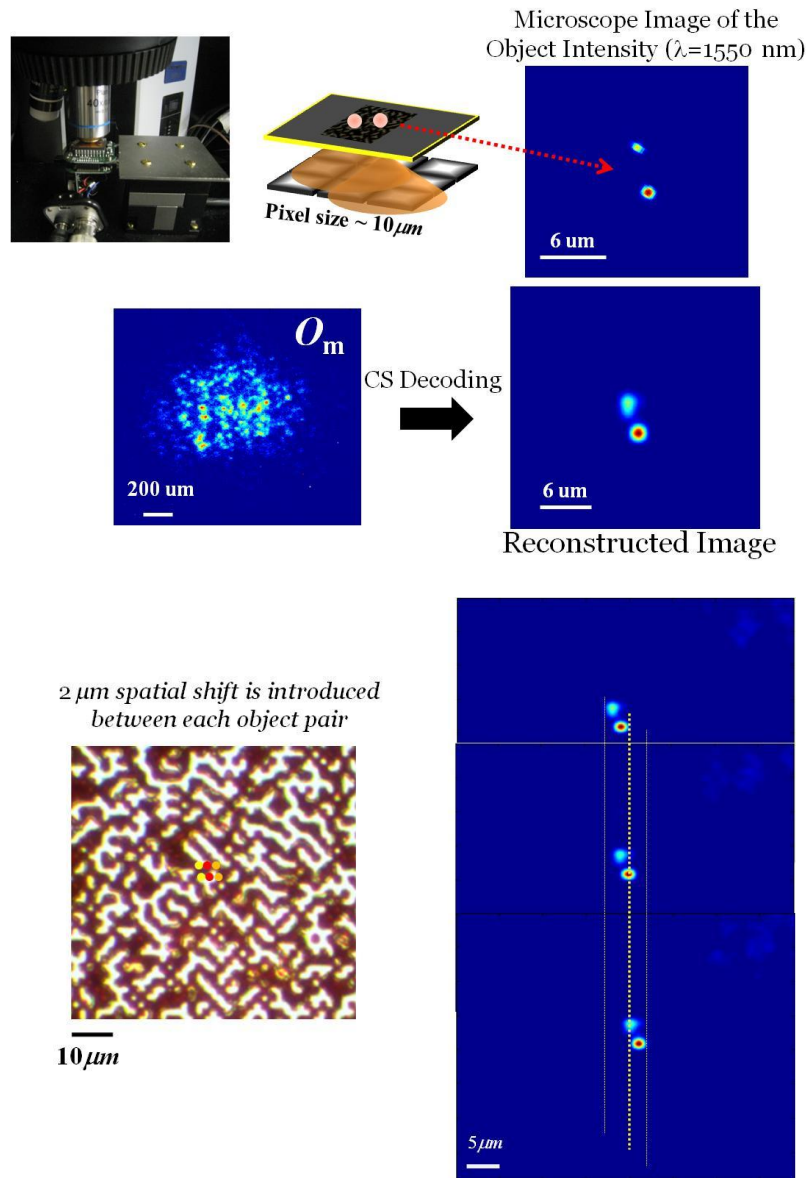
These proof-of-concept experiments were made in IR as well as visible parts of the spectrum, however the core idea and the mathematical principles behind this approach are also applicable to other parts of the electromagnetic spectrum to computationally enhance the performance of opto-electronic sensor-arrays that are designed to operate at various wavelengths.

For further details, please refer to our recent papers that are appended to the end of this report.

Archival publications (published) during proposal period:

Journal Articles:

1. B. Khademhosseini, G. Biener, I. Sencan, and A. Ozcan, "Lensfree Color Imaging On a Nano-structured Chip using Compressive Decoding," *Applied Physics Letters* DOI:10.1063/1.3521410 (2010)

2. B. Khademhosseini, G. Biener, I. Sencan, T. Su, A.F. Coskun and A. Ozcan, "Lensfree Sensing on a Micro-fluidic Chip using Plasmonic Nano-apertures," *Applied Physics Letters* DOI:10.1063/1.3521390 (2010)

3. B. Khademhosseini, I. Sencan, G. Biener, T. Su, A.F. Coskun, D. Tseng, A. Ozcan, "Lensfree On-chip Imaging using Nano-structured Surfaces," *Applied Physics Letters* 96, 171106; doi:10.1063/1.3405719 (2010)

Conference Proceedings:

1. B. Khademhosseini, G. Biener, I. Sencan, A. Ozcan, "Lens-free, near-infrared (NIR) imaging using structured substrates and compressive sensing," SPIE Defense, Security and Sensing, April 26, 2012, Baltimore USA

2. B. Khademhosseini, I. Sencan, G. Biener, T. Su, A.F. Coskun, D. Tseng, and A. Ozcan, "Incoherent lensfree imaging on a chip using compressive decoding of nanostructured surfaces," SPIE *Photonics West,* Nanoscale Imaging, Sensing, and Actuation for Biomedical Applications VII, January 2011, San Francisco, CA, paper # 7908-21

3. B. Khademhosseini, I. Sencan, G. Biener, T. Su, A.F. Coskun, D. Tseng, A. Ozcan, "Lensfree Incoherent Microscopy on Nano-Structured Chips," BMES Annual Meeting, October 6-9 2010, Austin Texas USA

Changes in research objectives, if any: None

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Extensions granted or milestones slipped, if any: None

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